THE TREND OF RESEARCH AND TECHNOLOGY OF SENSING AND EXTINGUISHING BUILDING FIRES IN THE U.S.A.

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The first step in identifying trends is retrospective, and the second is an examination of the present state, from which predictions can be ventured. The 50th anniversary of the Japanese National Research Institute for Fire and Disaster (formerly the Fire Research Institute) is a most appropriate occasion to assess the trend for fire sensing and extinguishment from a United States perspective.

Retrospective

What technologies were available in the U.S. for automatic detection and suppression of fires fifty years ago? Foremost was the traditional water sprinkler. Here was a fully integrated detection/suppression system elegant in its simplicity, with no electrical connections, only one moving part, minimum maintenance, and a history of reliable, effective suppression. Fire detection systems, including the sprinkler link, were primarily thermal in principle, and some were tied into a local audible alarm. Fire extinguishers contained water, CO_2, or powder, and normally were dispensed manually. More sophisticated detectors (thermal and radiation) and exotic gases [carbon tetrachloride (CCl_4) and chlorobromethane (CH_2ClBr)] were under development during and following World War II to increase the protection of military vehicles and aircraft.

Few residential and office buildings were protected by automatic detection/suppression systems of any type and there was no pull from the construction industry to conduct research to change that situation. Sprinkler designs had evolved incrementally for over 60 years and were extremely effective in suppressing fires in industrial settings. The fire protection industry had little need to invest in research because of this success. The pull for new technology was primarily from the military and aviation sectors.

The trends for fire detection and suppression technology fifty years ago could have been gleaned from the tea leaves of the following activities:

- the development of the ionizing radiation chamber/cold cathode tube detector
- general developments in electronics (the computer and transistor)
- transfer of sensing technologies from the military to civilian applications
- research into halons and other chemical agents
- risk reduction by the insurance industry
- propulsion research

The invention of the cold cathode tube in the 1940s allowed Meili [1] to produce the forerunner of the modern ionization smoke detector. The transistor furthered development of all detectors that relied on the amplification of an electrical signal. The power of dedicated computer chips is just now being incorporated directly into detection hardware, although the computer, itself, has been an indispensable tool over the decades for gaining an understanding of fire dynamics and suppression chemistry. Military applications are a natural stimulus for sensor research. The hostile environment, the need for fast response times, and the deep-pockets of the government to fund these activities led to exotic technologies, a fraction of which have migrated to the civilian building sector.

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The role of the military is similar for the development of fire suppressing chemicals and technologies. Most of the research done in the first decade following the war was sponsored by the Department of Defense to identify less toxic alternatives to the prevailing halocarbons. The Purdue study [2] is worth particular mention. Ford [3] provides a review of other research milestones during this early period which led to the miracle compound, bromotrifluoromethane (CF_3Br), also known as halon 1301.

A major drawback with sprinklers of 1940s vintage was the large quantity of water released and the concomitant damage. Factory Mutual was motivated to reduce the risk of fire when it took on the mission of improving the performance of sprinkler systems through an aggressive program of research. Key results of the first sixteen years of activity are summarized in the monograph by Thompson [4]. A comprehensive review of the sprinkler technology developments up through 1996 is provided by Yao [5].

Ignition, sustained combustion and flame extinction are all topics that fire science has in common with combustion sources of power production and propulsion. Research into the intricacies of the combustion process to improve our understanding of chemical kinetics, turbulence, spray dynamics, detonations, and flame radiation have led to practical improvements in engine efficiency, reduction in knock, emission controls, and power output and turn-down ratios. The early driver for this research was not the building industry, but the defense, automotive, and aircraft industries. It is safe to say that fire detection and suppression were not on the minds of combustion researchers and technologist at that time, but the building fire protection community has reaped some of the benefits.

Present State of Fire Detection Research

Fire detectors are now ubiquitous in the U.S., protecting constructed facilities of all types including single family dwellings, commercial and retail buildings, industrial installations, government complexes, and transportation systems. The ionization smoke detector has gone from the scientist's bench to the hardware store, with a purchase cost under five dollars. Multi-sensor detectors are being installed in commercial installations, high sensitivity aspiration systems are in use protecting critical equipment, and techniques are being incorporated to reduce the incidence of false alarms through more intelligent signal processing and better communication systems.

Current research focuses on quantifying the environment in which the detector sits, under both a fire and non-fire situation. New sensing principles are being investigated, along with better ways to collect and interpret the information from the sensor. An overview of recent developments in the U.S. in fire detection is presented elsewhere in these Proceedings [6]. The following paragraphs highlight significant research activities directed towards building applications.

The emissions from normal and abnormal cooking situations were measured and the responses of conventional and research-grade sensors were collected by Johnsson [7] to determine the feasibility of developing a pre-fire detector that could turn off a cooking device in time to prevent flaming combustion. While no single sensor performed faultlessly, it was concluded that pre-fire detection systems are physically feasible and merit further consideration. A two wavelength, near IR sensor was developed by Lloyd et al. [8] to respond to radiant emission either directly from a small fire or to IR reflected from the walls and ceiling, permitting the system to detect fires not in the line-of-sight or even in the same room. A prototype was constructed and shown to respond properly to the CEN 54 [9] flaming fires, but to be unable to detect the smoldering fires unless viewing them directly. Open-path FTIR methods were examined [10] to determine the trade-offs between the quality of the optics (i.e., price) and the sensitivity of the system to detect different fires and non-fire situations. The rich amount of information in the transformed IR spectrum is sufficient to ascertain a fire from a non-fire, but the investigators have not yet come up with a practical, moderate price detection system suitable for anything other than very specialized industrial applications. Fiber-optic coupled diode lasers have been demonstrated [11] to be able to sense low concentrations of combustion products (e.g., CO, CO_2, O_2, NO, CH_4). Current research is aimed at determining the limits of multiplexing signals from hundreds of individual fibers so that a single laser can be used to monitor an entire building. This is necessary to bring the cost within reason.

An algorithm which computes the source temperature and uses the frequency content of the time varying radiant emission was developed [12] in connection with the near IR sensor described above to discriminate fires quickly and assuredly from background radiation sources. An inverse problem solution method was used [13] to locate a fire to within a square meter and its heat release rate (to within a factor of two) from knowledge of the time that liquid crystal sensors, viewed with a video camera, changed color. Combinations of CO and smoke sensors were exposed to different fire and non-fire situations [14] in order to develop an alarm algorithm that could effectively discriminate between actual fire and nuisance conditions. The response of a host of gas, smoke and temperature sensors was used to train a neural network [15,16] to determine the presence of a fire in a nuisance-laden environment. Data fusion methods were applied in another study [17] to interpret the signals from multiple conventional smoke detectors and to formulate an appropriate response to one or more indications that a fire may be present.

Special hazards often require specialized fire detection solutions. Fires in aircraft hangars have to grow to a considerable size before conventional thermal sensing elements in sprinklers activate due to the large volume, high ceiling height, and the possibility of cross winds from open doors. A full scale study on the behavior of multiple detection systems exposed to burning pools of jet fuel was undertaken to develop new guidelines for U.S. Navy hangar installations [18]. A workshop was held at NIST [19] to identify the sources of and possible remedies for false alarms in telecommunications facilities. These systems qualify as special hazards because they maintain critical communication links, they cannot be readily de-energized, and they are highly susceptible to collateral damage.

Numerical modeling of the response of a detector to the early stages of a fire continues to be a significant area of research. The capability of zone and field models to predict the response of thermal elements in the aircraft hangar tests described above were compared in reference [20]. A general assessment of fire detection models available to the practicing engineer was made by Schifiliti and Pucci [21], and Madrzykowski gave a status report [22] on the evaluation of DETACT. The fire-emulator/detector-evaluator [23] is being designed as a link between the numerical models and laboratory test methods. The FE/DE is capable of providing a concentration of CO, CO_2, black smoke, velocity and temperature which correspond to the conditions surrounding a fire detector mounted at an arbitrary distance from the plume of a standard fire (e.g., CEN 54 [8]). Tests are currently underway to establish the response time of commercial smoke detectors to small changes in environmental conditions, which will be used to develop algorithms for insertion into general zone and field models. The FE/DE also serves as a test-bed for nuisance source discrimination and sensing algorithm developments.

Present State of Fire Suppression Research

Water-based systems remain, by far, the most popular for automatic fire suppression. Sprinkler technology continues to evolve, with research focusing on faster and more predictable response to a growing fire. Additives to water and foams are being investigated to improve performance. Interest continues in the behavior of fine water sprays and the application of water mist systems to a wider range of fire threats. The search for alternatives to halons dominates the fire suppression research agenda; however, most applications are not directed towards buildings. Included is work on dry powders, inert gases, halocarbons, propellant gas generators, and inorganic metallic compounds. Specific research projects on aqueous and halon replacements which could impact building fire protection are discussed below. Grosshandler [6] and Gann [24] review additional work on suppression elsewhere in these Proceedings.

The heat transfer to a sprinkler head and the influence of recessing the head in the ceiling have been studied [25,26]. Current NIST research focuses on the experimental measurements of drop sizes in typical commercial sprinklers to provide data for validations of drop dynamics calculations in predictions of fire growth and suppression in a simulated industrial warehouse filled with stacks of commodities [27]. Full scale rack storage fire experiments have been conducted by Factory Mutual [28,29] to determine the performance of early response sprinklers and the amount of heat absorbed by the water during the suppression of cardboard commodities. A demonstration was held at NIST [30] to highlight new technologies that are effective in suppressing fires even with a limited supply of water. The special problem of water leakage through elevators following the activation of a sprinkler was also examined [31]. Fire protection foams continue to receive attention because of their potential for much lower water use and increased effectiveness in liquid hydrocarbon and three dimensional fires [32,33].

Several issues regarding the applications of water mist to the control of enclosure fires have been recently discussed at the NFPA 750 *Water Mist Fire Suppression Systems* committee meeting. These include droplet size measurements, system reliability, fire suppression and control characterization, and test protocols and performance criteria. Hung and Yao [34] studied the interaction between fine water sprays and wires inserted into the flow to ascertain how the drop size distribution may be perturbed as the water mist flows over and through obstacles. The evaporation of a 300 μm drop of water was studied with and without fire suppression additives as it approached a heated surface [35]. The details of the interaction between fine water droplets and a flame front were examined [36] in a counter-flowing diffusion flame. A finite difference model of the fluid and droplet dynamics was developed to explain the observations. A Quasi-steady model for fire suppression by water mists was suggested [37] to give a rough estimate of the performance in full-scale spaces. References [38,39] describe full-scale tests in specialized applications: library shelve storage and wet bench protection.

Scientific studies on the chemistry of highly effective compounds, including CF_3I [40] and $Fe(CO)_5$ [41], are being conducted to determine the best routes to flame extinction. Babushok and Tsang [42] searched the literature to identify a large number of metallic compounds that appeared to be more effective flame inhibitors than CF_3Br. The toxic compound $Fe(CO)_5$ was listed as the most effective, but a number of more benign chemicals such as $CuCl_3$ and Na_2CO_3 were rated more than an order of magnitude more effective than CF_3Br. A combination of chemical and physical effects has been shown by Lott et al. [43] to allow one to reduce the amount of a less friendly compound in a binary mixture while maintaining a satisfactory level of flame suppression efficiency.

NFPA 2001, *Clean Agent Fire Extinguishing Systems*, is the industry guide for alternatives to total flooding agents like CF_3Br. It is currently undergoing revision to expand the number of chemical compounds listed, and to address operational concerns. One issue is the potential for halocarbons to produce high levels of acid gases during the suppression process

[44]. The U.S. Navy has found [45] that the implementation of a water spray following the discharge of a hydrofluorocarbon can substantially reduce the HF content, as well as the temperature, permitting much quicker reclamation of the space. The application of halocarbons to electrically energized equipment for which power cannot be removed prior to release of the agent is of great concern to telecommunications and computer facility operators. Depending upon power level and temperature of the electrically heated surfaces, a significant increase in the amount of agent over de-energized systems may be required [46].

Predicted Trends in Research and Technology Development

Continued research into fire detection and suppression in the U.S. is motivated by one or more of the following needs:

- to increase the ability of fire detectors, based upon current sensor designs, to discriminate a fire threat from a non-threatening change in the environment;
- to adapt emerging sensor technologies to extend capabilities of current fire detection systems;
- to increase the efficiency and applicability of automatic water suppression systems;
- to find suitable replacements for halons;
- to better protect special hazards; and
- to improve certification and predictive capabilities for detection and suppression systems.

The main pull from the building industry is for proven fire detection/suppression technologies that can be installed and operated at lower cost; enhanced performance capability is a lower priority, especially if the enhancement is associated with some risk. The U.S. detection systems manufacturers are following closely advances in sensor technologies, and would like to know more about the signatures of fires and nuisance sources. They are wary, though, of radical departures from the conventional ionization and photoelectric smoke detector design. The industries providing the major impetus for research into new detection technologies are those with special hazards or those impacted by changing regulations. Telecommunication central offices, computer network systems, aircraft cargo holds, manned space craft, and hazardous storage areas are examples of applications pulling for innovative fire protection solutions. A technology push is coming from smaller companies and aerospace industries previously unassociated with fire detection. These are typically companies at the cutting edge of sensor design and manufacturing, companies with expertise in knowledge engineering and/or communication systems, or companies who are pushing a technology originally developed for the military into a new, civilian application. For those spaces previously protected by halon 1301, the pull for suitable new suppression technologies is immense. Conventional sprinklers, clean agents currently on the EPA SNAP list [47], CO_2, dry powders, and *no* protection are all being considered, but in many applications none of these alternatives is suitable.

Research at the fundamental level will likely continue at a steady pace because our current knowledge is insufficient to predict the performance of existing detection technologies or suppression systems in anything other than idealized situations. Innovative sensing concepts, unconventional suppressants or unique combinations of detection and suppression systems cannot be designed, certified, or installed if we are unable to predict their behavior in the field. For this we need to understand the following: material behavior under heating and flaming conditions; dynamics of fire growth and smoke movement prior to and during suppression counter-measures; the consequences of fire and products of suppression on people, property and the environment; how to sense and discriminate low levels of emissions from pyrolyzing and burning materials; and how to sense and discriminate background sources of the same emissions.

An emerging trend in fire research is to focus on a particular fire-type in a specific application, and then to make use of all the available information and engineering tools to answer key questions about the performance of a detection/suppression system. This involves using the results of past work and current needs to properly frame the problem, conducting numerical simulations of the entire event using relatively coarse zone and field models to identify the most sensitive parameters, performing small scale well controlled experiments to develop empirical correlations of the most sensitive parameters, predicting the behavior of a full scale test with the most appropriate numerical models into which the empirical correlations have been imbedded, designing an instrument package for a large scale test of the same fire and geometry which will provide a meaningful comparison between the simulation and the test, conducting the full scale test paying close attention to parameters identified as being sensitive, and comparing the test to the simulation to learn from where they are different and where they agree. An example of this approach is presented by Evans [27].

Research is required to overcome barriers to the implementation of unconventional but promising new technologies, and to provide answers to complex, interrelated questions like What can be gained by sharing information among other building systems such as indoor air quality, heating and cooling, and/or security? Can sensing be used to actively control fire counter-measures during suppression and clean-up? or, How does one evaluate an integrated detection/suppression (and building control) system?

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